Minuteman: Forward Projection of Unmanned Agents Using the Airborne Internet[1,2,3]

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Abstract—In future battlefield operations, autonomous agents such as Unmanned Ground Vehicles (UGVs) and Unmanned Airborne Vehicles (UAVs) will be projected to the forefront for intelligence, strike, search and rescue and other tactical operations. The agents will be organized in clusters in order to carry out such missions; different clusters may execute different missions simultaneously. During the mission, the unmanned agents are supported by sensors on the ground and in the air, and can receive commands and send information back to a command ship, say. It is clear that *efficient communications* between agents, and from agents to sensors and to command posts are critical to mission success. The goal of the Minuteman project is to develop the concept and initial prototype of an agile, dynamic, multi-layer "Internet in the Sky" architecture that can deliver the "forward power" of the unmanned missions. The architecture consists of a high speed, wireless Mobile Backbone Network (MBN) – with point-to-point wireless links, and local access networks feeding to backbone nodes. The design is extremely challenging because of the hostile environment, the need for QoS support and the unpredictable, nature of the requirements. The focus of this paper is on scalable addressing and routing in such a multiplayer, mobile environment where UAVs can fly at speeds exceeding several hundreds miles per hour. We exploit the fact that agents typically move in groups, and achieve scalability by keeping track of a "landmark" for each group. This is done using LANMAR, a Land-Mark Ad hoc Routing scheme. The LANMAR scheme originally developed for "flat" ad hoc networks extends naturally to a network with a physical backbone. Via simulation we show that LANMAR maintains robust, resilient, rapidly restored connectivity in the face of agent mobility.

TABLE OF CONTENTS

1. INTRODUCTION AND ONR PROGRAM OVERVIEW

In future battlefield operations, autonomous agents such as Unmanned Ground Vehicles (UGVs) and Unmanned Airborne Vehicles (UAVs) will be projected to the forefront for intelligence, surveillance, strike, enemy antiaircraft suppression, damage assessment, search and rescue and other tactical operations. The agents will be organized in clusters in order to carry out such missions; different clusters may execute different missions simultaneously. A mission is generally assembled from various unmanned autonomous agents (UGVs, UAVs, etc). The missions must be carefully scheduled, equipped with adequate resources, coordinated and monitored until completion. During the mission, the unmanned agents are supported by sensors on the ground and in the air, and can receive commands and send information back to a command ship, say. It is clear that throughout the various mission phases (from planning to navigation, sensor intelligence gathering and forwarding, damage assessment, etc.), efficient communications between agents, and from agents to sensors and to command posts are critical to mission success

Addressing the above scenarios will be critical for the Navy. In fact, future naval missions at sea or shore will require effective and intelligent utilization of real-time information and sensory data to assess unpredictable situations, identify and track hostile targets, make rapid decisions, and robustly

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influence, control, and monitor various aspects of the theater of operation. Littoral missions are expected to be highly dynamic and extremely uncertain. Communication interruption and delay are likely, and active deception and jamming are anticipated.

Efficient system solutions to the above problems are currently investigated by the Office of Naval Research (ONR) in a comprehensive "Intelligent, Autonomous Networked Agents" program. ONR envisions unmanned systems to have a profound influence on future naval operations allowing continuous forward yet unobtrusive presence and the capability to influence events ashore as required. Unmanned vehicles have proven to be valuable in gathering tactical intelligence by surveillance of the battlefield. For example, UAVs such as Global Hawk are rapidly becoming integral part of military surveillance and reconnaissance operations. The goal is to expand the operational capabilities of UAVs to include not only surveillance and reconnaissance, but strike and support mission (e.g., command, control, and communications in the battle space) as well. This new class of autonomous vehicles is foreseen as being intelligent, collaborative, recoverable, and highly maneuverable in support of future naval operations.

The ONR approach is aimed at an integrated agent-based system-of-systems that embodies technologies that will permit unmanned systems to move away from platform-centric operations to network-centric operations, while exploiting knowledge and power of survivable tiered weapons and sensors combined with fully netted maneuver warfare and enabling the Navy to bring fully netted force to the battle space. Netted-Force, as shown in Figure 1, is the glue that pulls supporting technologies such as mission planning, path planning, reasoning, decision making, and distributed real-time computing and control together.

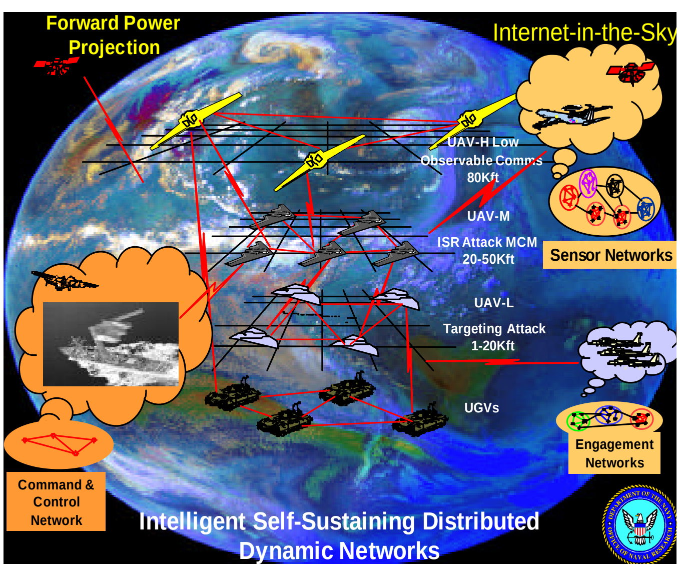


Figure 1 - Netted Force through Distributed Networks of Intelligent Agents

The development of netted-force hinges on three essential technologies:

(a) Robust wireless connectivity and dynamic networking of autonomous unmanned vehicles and agents,
(b) Intelligent agents including: mobile codes, distributed databases and libraries, robots, intelligent routers, control protocols, dynamic services, semantic brokers, message-passing entities, disembodied code,
(c) Decentralized hierarchical agent-based organization.

As Figure 1 illustrates, the autonomous agents have varying domains of responsibility at different levels of the hierarchy. For example, clusters of UAVs operating at low altitude (1K-20K feet) may perform combat missions with a focus on target identification, combat support, and close-in weapons deployment. Mid-altitude clusters (20-50K feet) could execute knowledge acquisition, for example, surveillance and reconnaissance missions such as detecting objects of interest, performing sensor fusion/integration, coordinating low-altitude vehicle deployments, and medium-range weapons support. The high altitude cluster(s) (50K-80K feet) provides the connectivity. At this layer, the cluster(s) has a wide view of the theater and would be positioned to provide maximum communications coverage and will support high-bandwidth robust connectivity to command and control elements located over-the-horizon from the littoral/targeted areas.

The hierarchical agent organization has architectural features useful for the design of the dynamic network architecture. Higher levels of the hierarchy mostly operate over a greater spatial extent but at slower time-scales. The reason is that the transfer of data over larger spaces usually requires more time, because data transfer requires multiple hops, and in a wireless environment, the reliability of a link can degrade rapidly with increasing range. Thus, stronger codes may be required at the expense of bandwidth. The bandwidth requirements could be derived from the space-time locus of data. Following are some of the essential communication requirements:

- **Secure communications** to deny information to hostile forces. This is particularly challenging because the envisioned strength of the autonomous agents stems from their ability to share information and perform distributed information processing and fusion;
- **Low Probability of Detection and Interception and Antijamming** capability in order to penetrate deep into hostile territory. Once AUVs are detected, hostile forces will attempt to disrupt the AUV's communication system with jamming techniques ranging from broadband noise to optimum fraction-of-the-band jammers;
- **Channel Capacity:** data quality, high throughput, and high performance, for example, low bit error rate, frame error rate, lost data, and delay;
- **Dynamic Network Resource Allocation:** reliability, redundancy, availability, interoperability of communication links to insure a high degree of

connectivity, e.g., alternate transmission routes and multihop communications, in hostile environments.

Functional flexibility and interoperability of the autonomous agents are essential to the overall mission effectiveness, that is, loss of or malfunction of individual agents should only result in marginal degradation of the mission. This self-healing/self-preservation characteristic relies on the autonomy, which includes redundant functionality, adaptation, and self-reconfiguration, as well as robust connectivity of the aggregate system through: (a) Distribution and reallocation of essential functions amongst the vehicles in a given cluster; and (b) Transfer of agents from one cluster to another.

These capabilities can only be realized through adaptable dynamic communication networks allowing reliable, secure, high throughput connectivity. These networks can be grouped as: (a) Intra-network for secure communications among the vehicles within the local network/line-of-sight; (b) Inter-network for secure communications between the vehicles in adjacent networks. Other significant and challenging issues are:

(a) **Adaptive Communications**. Agents' mission diversity and cooperative networking configurations coupled with the vehicles' dynamics and mobility will demand a communication infrastructure that is adaptive and dynamic. The architecture must accommodate adjustments to changing channels, network configurations, data requirements, and security. The focus is on developing adaptive connectivity techniques at various levels of the hierarchy, including the physical layer, network layer, data/information layer, and security layer. In contrast to non-adaptive schemes that are designed relative to the worst-case channel conditions, adaptive techniques take advantage of the time-varying nature of wireless channels. That is, in adaptive techniques the goal is to vary the transmitted power level, symbol rate, coding rate/scheme, configuration size, or any combination of these parameters in order to improve the link performance which includes data rate, latency, and bit error rates (BER), while meeting the system performance specifications. Adaptive modulation has been shown to increase the data rates on flat-fading channels by a factor of five or more. Additional coding can be used to obtain a reduction in transmit power or BER or to increase resistance to jamming. Moreover, the BER in adaptive modulation remains constant independent of channel variations, which greatly improves reliability of the wireless link.

(b) **Adaptive QoS**. Adaptive protocols that adjust to a specific mission or application, or can secure an acceptable end-to-end performance will be required. Adaptation may take the form of variable-rate or multi-resolution compression, variable-rate error correction coding, and message prioritization relative to delay constraints.

The rest of the paper is organized as follow. In section 2 we review the MINUTEMAN project. In section 3, we introduce a scalable Mobile Backbone Network (MBN) infrastructure. We address the dynamic Backbone Node (BN) election problem and introduce a new stable clustering scheme in section 4. In section 5, we present the LANMAR routing extension to the MBN. In section 6, our clustering scheme is compared with other popular ones regarding stability and our routing scheme is evaluated in a large-scale ad hoc network. Related work is given in section 7. Section 8 concludes the paper.

2. THE MINUTEMAN PROJECT

The goal of the Minuteman (Multimedia Intelligent Network of Unattended Mobile Agents) project, recently funded by the Office of Naval Research, is to develop the concept and initial prototype of an agile, dynamic "Internet in the Sky" architecture that can support the demanding communications requirements of the agents and can deliver the "forward power" of the unmanned missions. Here, we briefly describe the challenges that such Internet in the Sky design poses in the face of the unique requirements of the unmanned missions. We also outline the innovative approaches that we plan to undertake in order to meet such challenges.

The first challenge is to handle **agent mobility**, which will vary from the roving speed of the UAGs all the way to the hundreds of miles per hour speed of airborne assets (UAVs) during an attack mission. The traditional Mobile IP approach will not scale to large number of mobile agents, high speeds and pervasive mobility: the registration of the mobile with Foreign Agents introduces excessive overhead and the rerouting via Home Agent and Foreign Agent becomes impractical. Our approach will be to embed mobility support at OSI layer 2, using ad hoc networking and ad hoc routing, below IP (we will still retain, however, the Mobile IP paradigm for communications with the wired Internet). Moreover, we will exploit the fact that agents typically move in, and will achieve scalability by keeping track of group rather than individual movements. Our scalable approach to group mobility management and routing has been implemented in the LANMAR (Landmark ad hoc routing) architecture [18]. For the MBN network the LANMAR architecture has been extended to large node populations and large geographical distances using multi-layering (ie, backbone) concepts. In the paper, we will present initial LANMAR results for representative scenarios. We will evaluate the ability of LANMAR to maintain robust, resilient, rapidly restored, nearly optimal (in terms of path length) connectivity in the face of agent mobility.

The robust, all-time connectivity provided by LANMAR is critical, but it is not sufficient to carry out successful missions. The UAVs gathering intelligence at the forefront must be able to transmit multimedia (eg, compressed video) streams with bandwidth guarantees across the backbone network to other clusters of mobile agents preparing the attack; or, to the commander on the ship. Thus, a second important challenge for the airborne Internet is to support **Quality of Service** in terms of bandwidth, response time delay, and delay variation. We are planning a multi-layer approach to QoS that will include backbone beam forming at the radio layer, MAC layer scheduling, network layer QoS routing, Call Acceptance Control and backbone path pinning by means of label switched paths and MPLS (Multi Protocol Label Switching). MPLS will provide the flexibility to forward individual and/or aggregated flows on QoS compliant multiple paths selected by the QoS routing algorithm, overcoming the limitations of traditional shortest path routing. These concepts are implemented in the "Mobile Backbone Network" architecture that builds upon the LANMAR connectivity management and provides QoS where needed. QoS support requires the allocation and "alignment" of several network resources (eg, backbone UAVs in strategic positions). If the UAVs are destroyed or reassigned to a more critical mission, QoS will be gracefully degraded, possibly all the back to basic LANMAR connectivity.

A third critical requirement of our architecture is to dynamically **adjust to environment changes** that are either due to natural causes (eg, radio propagation irregularities, fading, mobility, obstacles, battery power depletion, etc) or to enemy actions (eg, UAV destruction, radio jamming, etc). In view of such abrupt and often unpredictable changes, network protocols and applications must react in concert and must adaptively readjust to the new situation. We will discuss various adaptive protocol features (both intra and interlayer) that are being designed in our architecture, specifically to address these changes. Moreover, the total unpredictability of these changes makes it impossible to provide "guaranteed" QoS, as it is generally done in commercial networks. Instead, the concept of guaranteed QoS is replaced by that of "adaptively renegotiable" QoS. In the paper we will elaborate on a particularly important example of adaptation in the battlefield, namely, the adjustment of compressed video (say, MPEG 4) parameters in order to make best use of the existing network resources.

Dynamic adaptation is also required in the assembly of resources to launch a mission and to track its progress. In this respect, the unique feature of the unmanned agent system is that some agents can support multiple functions. For example, a UAV can be used for communications, as a node of the Mobile Backbone Network; as well as for intelligence, to gather video and images as part of a scouting mission. Thus, planning a mission requires the allocation of limited resources and possibly the "reallocation" of resources from background missions to top priority missions. Monitoring and dynamic reallocation of resources based on time changing priorities, along with QoS renegotiation, is performed by a distributed, systems wide Adaptive Resource Monitoring and Management Network (ARMMNET). ARMMNET will permit to dynamically reallocate across multiple simultaneous missions the various battlefield resources (from communications to CPU power, memory and databases) in the most efficient manner.

Advanced applications such as Automatic Target Recognition (ATR) require the gathering of video and sensor information from vast areas in the battlefield in order to determine presence and type of targets. This information must be received with extremely tight accuracy and time constraints in order to execute a successful strike mission, say. Brute force scanning of the entire area may not be feasible – it may require too much time given the available UAV and sensor assets. In order to accomplish the goal within the required constraints, we propose to maintain a **distributed Information Database** that can provides global information about assets in the battlefield as well as video and images captured during routine surveillance. The Information Database will permit to "guide" UAV clusters in the search to the critical areas and to supplement the UAV and sensor image data with stored information, thus reducing the time to target detection and recognition. The maintenance of a timely and accurate Information Database in our environment poses several new challenges, including: distributed, fault tolerant implementation; ability to answer queries with variable degree of accuracy depending on time constraints; and, careful tradeoff between the background refresh rate (and thus accuracy) and the use of limited communications and sensor resources.

The dynamic adaptation to the unpredictable, hostile environment requires the support of advanced, **programmable radios** and of adaptive modulation and channel encoding schemes. The goal here is to achieve the best use of the available spectrum while providing the radio range, beam directivity and channel quality required by the upper protocol layers. An important contribution of this project will be the development of "modular" radios that utilize advanced MIMO and OFDM techniques and can be dynamically reconfigured to fit the needs of a low power stationary sensor as well as the challenging demands of a fast flying UAV with video capture.

Finally, the demonstration of our highly adaptive suite of protocols will itself be a challenge. It will not suffice to demonstrate each component in isolation: the key is the successful interoperation of the components and the cooperative, interlayer adaptation to unpredictable changes in the environment. To this end, we will develop a novel, "**hybrid" simulator capability** that will allow to interface "real" applications to simulated innercore network protocols for a widely ranging set of configuration parameters (number of nodes, speeds, etc). The hybrid simulation testbed will be an essential complement of the hardware testbed which is by practical necessity limited in number, speed and geographic scope.

In summary, the adaptive, unmanned agent "Internet in the Sky" project will require an unprecedented degree of adaptivity in the design of the various protocol layers, from radio to applications, and the development of new adaptive middleware (ARMMNET) and new hybrid simulation techniques for testbed deployment and evaluation. As the trend in modern communications systems, both military and civilian, is to become increasingly more complex, autonomous and "adaptive", we believe that our unique, innovative solutions can be effectively transferred in the future to several other application domains.

The project has begone in Dec 2000. Progress has been reported in all the above mentioned tasks. In this paper we focus on scalable routing in the MINUTEMAN multilevel network architecture consisting of a high speed mobile backbone and of local access subnetworks feeding to each of the backbone nodes. A companion paper in this session describes the Backbone Network design philosophy. Our paper introduces a very flexible, scalable routing solution that handles mobility and can work on top of any arbitrary network infrastructure (eg, physical backbone network) and any "local scope" routing scheme**.** We exploit the fact that agents typically move in groups, and achieve scalability by keeping track of a "landmark" for each group. This is done using LANMAR, a Land-Mark Ad hoc Routing scheme. The LANMAR scheme was originally developed for "flat" ad hoc networks; but, it extends naturally to a network with a physical backbone.

3. AD HOC SCALABLE ROUTING

The ad hoc wireless networking technology shows great potential and importance in many situations because of its independence of a fixed infrastructure and its instant deployment and easy reconfiguration capabilities. Usually, a mobile ad hoc network (MANET) is assumed to be homogeneous. However, a flat ad hoc network has poor scalability[1][2][11]. In [1], theoretical analysis implies that even under the optimal circumstances, the throughput for each node declines rapidly toward zero while the number of nodes is increased. This is proved in an experimental study of scaling laws in ad hoc networks employing IEEE 802.11 radios presented in [2]. The measured per node throughput declines much faster in the real testbed than in theory. Simulation results in [10] also demonstrated that while routing protocols are applied, their control overhead would consume most available bandwidth when the traffic is heavy. Besides limitation of available bandwidth, the "many hop" paths in large-scale network are prone to break and cause many packet drops. Packet drop can be treated as waste of bandwidth and worsen network performance. All these issues prevent the flat ad hoc network from scaling to large-scale. Thus, a new methodology is needed for building a large-scale ad hoc network. An emerging promising solution is to build a physically hierarchical ad hoc network and mobile wireless backbones.

Our proposed hierarchical ad hoc network structure is called an ad hoc network with mobile backbones (MBN). A general picture of a two level MBN is demonstrated in Figure 2. Among the mobile nodes, some nodes, named backbone nodes (BNs), have an additional powerful radio to establish wireless links among themselves. Thus, they form a higher-level network called a backbone network. Since the backbone nodes are also moving and join or leave the backbone network dynamically, the backbone network is exactly an ad hoc network running in a different radio level. Multilevel MBNs can be formed recursively in the same way.

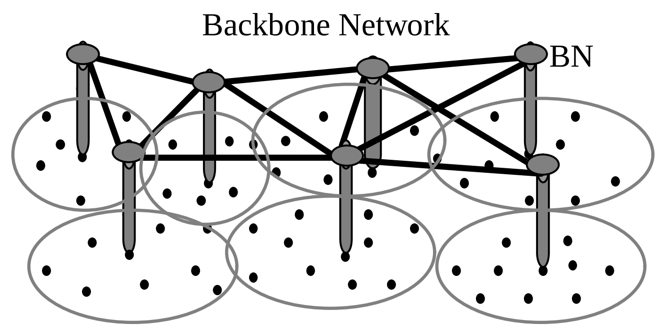


Figure 2 - General model of a two-level MBN

Three critical issues are involved in building such a MBN: (1) the optimal number of BNs; (2) BN deployment, and; (3) routing. Assuming that the number of BNs has been determined, the second important issue is how to deploy them in the field. The main challenges in carrying out an efficient deployment are mobility and BN failures. Using a clustering scheme to elect the BNs is a natural choice since clustering has been widely used in the past to partition nodes into small sets and to form hierarchical networks [6][7]. However, a major drawback of current clustering schemes is cluster instability in the face of mobility [6]. Unstable clusters lead to frequent cluster head changes and thus backbone node changes. The backbone topology would then be too dynamic to be tracked by routing and too unpredictable to be relied upon for QoS support. In the sequel, we will present a new fully distributed clustering scheme that achieves good stability.

Routing also critically affects the hierarchical network performance. Simply stated, routing must utilize the wireless backbone links efficiently. The main challenge that sets wireless networks apart from the wired Internet is mobility: in an Internet like routing scheme address prefixes would need to be continuously changed as nodes move! The overhead associated with address management would easily offset the routing control traffic and routing table size reductions offered by the hierarchical structure. Landmark Ad Hoc Routing (LANMAR) has proven to be a very effective scheme in large networks with group mobility [17][18]. In this paper, we extend LANMAR to the MBN architecture. The extended version retains the simplicity of

the traditional “flat” scheme. Yet, it preserves all the typical backbone strategy benefits, namely, short paths to remote nodes, low end-to-end delay, high quality links, augmented network capacity, and enhanced QoS support. Moreover, LANMAR exploits the hierarchical structure by reducing control overhead and propagating routing information more promptly.

4. BACKBONE NODE DEPLOYMENT AND CLUSTERING

One way to deploy the backbone network is to pre-compute first the optimal number of backbone nodes (BNs) required by the given initial node layout. Then, one distributes the BNs uniformly in the field at initialization. However, this 2-step procedure has two problems. First, the BNs move, thus after a while, some BNs may collide or anyway interfere with each other; while some areas may be uncovered. Secondly, BNs may fail or even be destroyed. New BNs must be deployed to replace the failed ones. A static, a priori allocation and deployment cannot efficiently fulfill both requirements.

Our proposed solution is to combine allocation (of number of BNs) and deployment by initially assigning *redundant* backbone capable nodes and letting the *election* procedure choose the active backbone set dynamically to meet the changing requirements. A node is backbone capable if it has the physical radio capacity to communicate with other backbone nodes and join the backbone network. If the backbone capable nodes are redundant, ie, are in more ample supply than strictly needed, only a subset of them joins the backbone at any given time. The remaining candidates are kept as spare nodes. When one BN is destroyed or moves out of a certain area, a new BN will be dynamically selected from the backbone capable set to replace it. If two backbone nodes move too close to each other, one of them will give up its backbone role.

The procedure to select backbone nodes from capable nodes is called *backbone election*. It should be dynamically performed. It should lead to a proper number of backbone nodes uniformly covering the entire area. Clustering has been traditionally used to select subset of nodes. In fact, it was also proposed to form “logical” ad hoc network hierarchies [6][7]. Here, we will use it to create a “physical” hierarchy. In the sequel, we briefly review some options and then introduce our solution.

Random Competition based Clustering (RCC)

Many clustering schemes have been proposed in the literature [3][4][5][6]. Among them, the Lowest ID (LID) and Highest Degree (HD) algorithms are widely used due to their simplicity. The detail of the two algorithms can be found in [3][4]. Previous research in clustering mainly focuses on how to form clusters with a good geographic distribution, such as minimum cluster overlap, etc. However, stability is also an important criterion, especially when clustering is used to support routing. In particular, in our hierarchical structure, stability of backbone nodes is a must. Previous clustering schemes cannot meet such a requirement.

Targeting both stability and simplicity, we have designed a new scheme called Random Competition Clustering (RCC). The main idea is that any candidate node, which currently does not belong to any cluster, can initiate a cluster formation by broadcasting a packet to claim itself as a cluster head. The first node, which broadcast such a packet, will be elected as the cluster head by its neighbors. All the immediate neighbors, after hearing this broadcast, give up their right to be a cluster head and become members of the cluster. Cluster heads have to periodically broadcast a cluster head claim packet to maintain their status. Since there is a delay from when one node broadcast its cluster head claim packet to when this packet is heard by its neighbors, several neighbor nodes may broadcast during this period. To reduce such concurrent broadcasts, we introduce a random timer. Each node defers a random time before its cluster head claim. If it hears a cluster head claim during this random time, it then gives up its broadcast. The idea of “first claim node wins” (independently of ID number or connectivity degree) was first proposed in the Passive Clustering scheme in [8]. The First Claim Wins scheme favors the Cluster Head, which can be challenged only by preexisting Cluster Heads. In Passive Clustering, clusters are formed on demand, when user traffic is present. In absence of traffic, the clusters are dissolved. Our scheme is active clustering (as the election is carried out continuously in the background); but we nevertheless use the same concepts of “first declaration” and explicit random timer. Of course, the random timer cannot completely solve the concurrent broadcast problem. When the concurrent broadcasts happen, we use the node ID to solve the conflict. The node with lower ID will become the cluster head.

Our Random Competition based Clustering (RCC) scheme is more stable than traditional clustering schemes such as LID and HD. In the LID scheme, when the cluster head hears a node with a lower ID, it will immediately give up its cluster head role. Similarly, in the HD scheme, when a node acquires more neighbors, the cluster will also be reconfigured.

Due to node mobility, such events happen very frequently. In RCC, one node only gives up its cluster head position when another cluster head moves near to it. Since cluster heads are usually at least two hops away, clusters formed by RCC are much more stable.

The low control overhead of our scheme is clear. In the lowest ID and highest degree clustering schemes, each node has to know the complete information of neighbor nodes. In our scheme, only the cluster heads need to broadcast a small control packet periodically. All other nodes just keep silent.

Multihop Clustering

Usually the clustering schemes are one hop based, that is the cluster head can reach all members in one hop. This is not suitable for backbone node election. We want to control (and in fact optimize) the number of elected BNs. To achieve this, we extend our clustering scheme to form K-hop clusters. Here, K-hop means that a cluster head can reach any one of its members in at most K hops. By adjusting the parameter K, we can approximately control the number of cluster heads. Bigger K means fewer cluster heads, thus fewer BNs.

In K-hop clustering, each node forwards the cluster head claim packet received from its cluster head. A mobile node will select the nearest cluster head within its K-hop scope to be its cluster head. If there is no cluster head within a K-hop scope, a node claims itself as a cluster head after deferring for a random time. In K-hop clustering, the probability of concurrent cluster head claims is relatively high due to the longer time for propagating cluster head claim packets K-hops away. The random time delay plays a very important role here.

5. Scalable Routing Scheme

After the BNs are elected, powerful backbone radios are used to connect BNs and form a backbone network. Now, the critical issue is routing. The backbone links among BNs provide "short cuts" and high bandwidth. Routing must be able to exploit backbone links for remote destinations. Moreover, since BNs may fail or even be destroyed, routing must be reliable and tolerant of such failures. In this section, we introduce Landmark Ad Hoc Routing (LANMAR) [17][18] and propose to extend it to include also the MBN, yet preserving its scalability and fault tolerant properties.

Landmark Ad Hoc Routing (LANMAR)

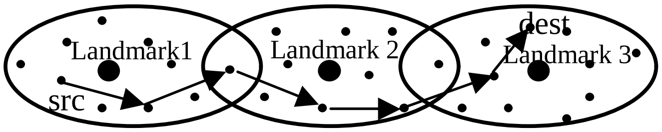
LANMAR is a scalable routing protocol for large, mobile, "flat" ad hoc wireless networks [17][18]. It assumes that the network is grouped into logical subnets in which the members have a commonality of interests and are likely to move as a "group" (e.g., a team of co-workers at a convention; or tanks in a battalion, or UAVs in an unmanned scouting mission). The existence of such logical groups can be efficiently reflected in the addressing scheme. We assume that a two level, IP like MANET (Mobile Ad hoc NET) address is used consisting of a group ID (or subnet ID) and a host ID, i.e. <Group ID, Host ID>. The group ID may change from time to time as a node is reassigned to a different group (e.g. task force in a military scenario). The Host ID is fixed and typically corresponds to the hardwired device address. Such MANET address uniquely identifies each node in the network (though it is possible for a node to belong simultaneously to more then one group and thus has more than one address). Similar to an IP network, the packet is routed to the group first, and then to the Host within the group. The challenge is "find" the group in a large, mobile network.

LANMAR uses the notion of landmarks to keep track of such logical groups. Each logical group has one node serving as "landmark". The landmark advertises the route to itself by propagating a Distance Vector, e.g. DSDV (Destination Sequences Distance Vector) [15]. Further, the LANMAR routing scheme is always combined with a local routing algorithm, e.g. Fisheye State Routing (FSR) [20]. FSR is a link state routing algorithm with limited "scope" feature for local, low overdead operation. Namely, FSR knows the routes to all nodes within a predefined Fisheye scope (eg, 3 hops) from the source. For nodes outside of the Fisheye scope, the landmark distance vector must be inspected for directions. As a result, each node has detailed topology information about nodes within its Fisheye scope and knows distance and routing vector (ie, direction) to all landmarks.

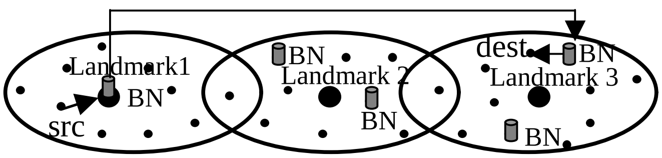
When a node needs to relay a packet to a destination is within its Fisheye scope, it obtains accurate routing information from the Fisheye Routing Tables. The packet will be forwarded directly. Otherwise, the packet will be routed towards the landmark corresponding to the destination logical subnet, which is read from the logical address field in the MANET address. Thus, when the packet arrives within the scope of the destination, it may be routed to it directly without ever going through the landmark.

LANMAR in the Mobile Backbone Network

In the original LANMAR scheme, we route the packet toward the corresponding remote landmark along the (typically long) multi-hop path advertised by the Distance Vector algorithm. If there is an MBN, the min hop path will generally include some of the Backbone links. Thus, in practice we route the packet to the nearest BN. This local BN then forwards the packet to a remote BN near the destination landmark via the backbone. Finally, the remote BN delivers the packet to the remote landmark or directly to destination if it is within its Fisheye scope. This will greatly reduce the number of hops. This procedure is illustrated in Figure 3. We can see that by utilizing the backbone links, the 6 hop path is reduced to be 3 hops long, a great improvement! Note that the routing within the MBN need not be DSDV. In fact, in the Minutemen project, MBN routing is a form of QoS as described in a companion paper in this session. The Landmarks are mapped to BNs (multiple mappings are possible for fault tolerance). The route within the MBN is computed by the MBN unique routing algorithm and may, in fact, satisfy given QoS constraints.



LANMAR routing in ad hoc network without backbones



LANMAR routing in ad hoc network with backbones

Figure 3 - LANMAR routing in MBN

A possible implementation of the MBN/LANMAR scheme is as follows. First, all mobile nodes, including BNs, are running the original LANMAR routing on the "local" links via the short-range radios. This is the foundation for falling back to "flat" multi-hop routing if the MBN fails. Secondly, a BN will periodically broadcast its landmark map (ie, the landmark distance vector) to neighbor BNs via the backbone links. The neighbor BNs will treat this packet as a normal landmark update packet. Since this higher level path is usually shorter, it will replace the long multi-hop paths. From landmark updates the ordinary nodes thus learn the best path to the remote landmarks, including the paths that utilize the backbone links. Each BN needs to record the radio interface to the next hop on each advertised path in order to route packets through the correct radios later. As discussed earlier, the routing within the MBN need not be "shortest path"- it may in fact be QoS routing.

One important feature of the proposed routing scheme is reliability and fault tolerance. The ordinary nodes are prevented from knowing the backbone links explicitly. The backbone links are automatically learned via routing broadcasts from BNs. Now, suppose a BN of one group is destroyed by enemies, the shorter paths via this BN will soon expire. Then new landmark information broadcasted from other nodes will replace the expired information. Thus, in the worst case, routing in this group goes back to original landmark routing while other groups with BN support can still benefit from the backbone short cuts. When all backbone capable nodes are disabled, the whole network becomes a "flat" ad hoc network running the original LANMAR routing, which can still provide connectivity, yet at lower performance (longer paths; no QoS support).

In this paper we assumed a very simple DSDV routing scheme in the MBN, with omnidirectional antennas, neighbor discovery, and distance vector routing support to landmarks. This scheme is sufficient to provide "short cut" benefits across the backbone. More elaborate and efficient MBN configurations (e.g. point to point links) and routing schemes (e.g. Link State) are currently being investigated in the MINUTEMAN project, as described by a companion paper by Rubin et al. With MBN Link State routing, each BN can advertise the landmarks within its reach. A BN can then select the most cost effective route within the backbone to the intended destination. This makes QoS support possible.

LANDMAR AND IP ROUTING

LANMAR is a MANET routing protocol. As such, it only supports routes inside the ad hoc network. In order to route packets to/from the Global Internet, other mechanisms are required. In particular, each node is assigned an IP address (IPv4 or IPv6). This IP address is used by Corresponding nodes in the Global Internet to reach our mobile node using Mobile IP via the Home Agent and the Foreign Agent (FA). The FA is a Name Server in the ad hoc network, that provides the mapping from IP address to LANMAR address. Mobile nodes refresh the Name Server data base periodically as well as when they join a new group. In IPv6 the local address field becomes the MANET address, namely the LANMAR address. This helps remove the inefficiencies of Mobile IPv4 (tunneling and triangular routing). More details on this topic are found in the paper by F.Templin at al, also in this session.

6. SIMULATION EXPERIMENTS

In this section, we evaluate the efficiency of the clustering and routing solutions so far proposed. We use GlomoSim/Qualnet [16], a packet level network simulation platform for ad hoc networks based on the parallel language PARSEC. We begin with the Random Competition based Clustering (RCC) algorithm. We compare the stability of our algorithm with the Lowest ID (LID) and Highest Degree (HD) algorithms. Since we are targeting large scale networks, we deploy 1000 mobile nodes in a "terrain" of size 3200mX3200m. Each mobile node has an IEEE 802.11 wireless radio with transmission range 175m. The DCF mode of IEEE 802.11 is used and channel bandwidth is set to 2Mbps. The node mobility model is random waypoint mobility [14]. In our simulation, the pause time is kept as 30 seconds and we vary the mobility speed to observe the stability of clusters. Simulation time of each run is 6 minutes.

The stability of clusters includes two parts, the stability of the cluster head and the stability of the cluster members. These are measured by two different metrics: average lifetime of a cluster head and average membership time of a cluster member. In the MBN, average lifetime of a cluster head is exactly the average lifetime of a backbone node. In our simulation, we only implement the basic clustering scheme without considering the "gateway" node selection as in [3][4] etc.

Cluster Stability

Usually, clustering is performed to form one hop clusters. Thus, here we compare the stability of one-hop clusters. Again one hop means that the cluster head can reach all its

members in one hop. The simulation results are given in Figure 4 and Figure 5.

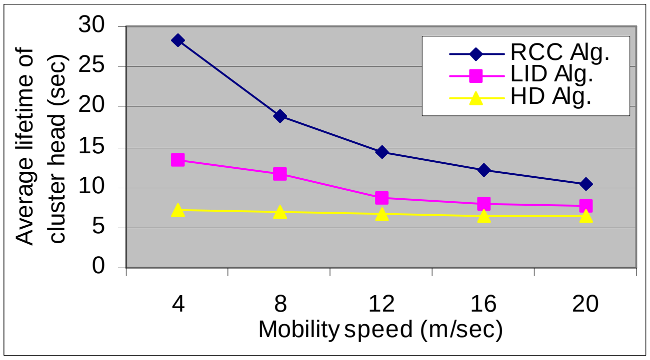


Figure 4 - Average lieftime of cluster head under mobility

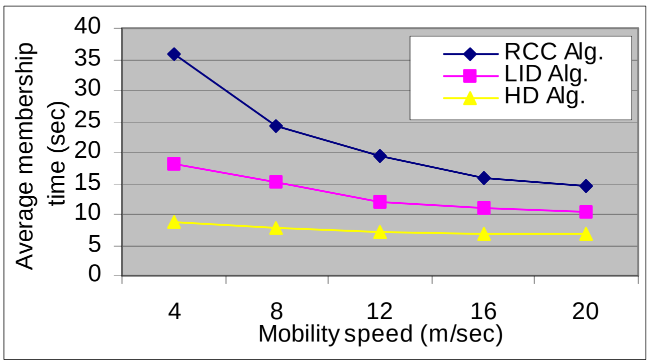


Figure 5 - Average membership time under mobility

From Figure 4 and Figure 5, we can see our clustering algorithm is more stable than the lowest ID and highest degree algorithms in both low mobility and high mobility scenarios.

Figure 6 and Figure 7 show cluster head and membership stability under the RCC algorithm when the hop scope of the cluster (ie, K-hop value) increases from 1 to 4. As intuitively expected, when the number of hops increases, the cluster becomes larger and thus more stable under the "first declaration wins" rule.

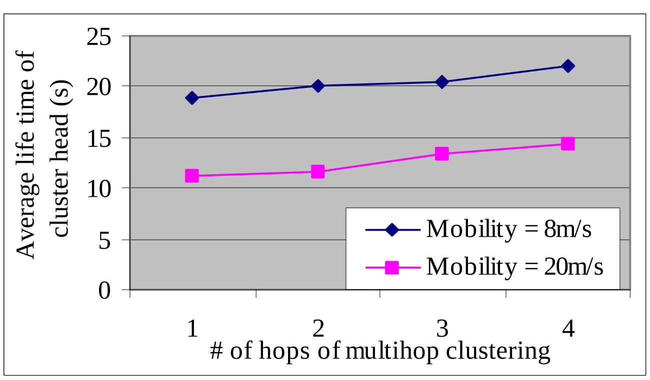


Figure 6 - Average lifetime of cluster head of multihop clustering

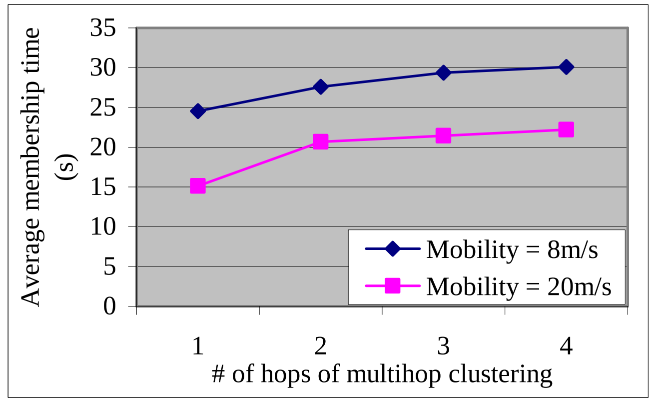


Figure 7 - Average membership time of multihop clustering

Routing Algorithm Performance

In this section, we compare the LANMAR extension in MBN with the original LANMAR routing and AODV[13], a popular on-demand routing protocol, in the flat ad hoc network. The basic environment is kept same as in the clustering experiment, i.e., 1000 mobile nodes. Each ordinary node has a small 802.11 wireless radio with power range 175m and channel bandwidth 2Mbps. The BNs have two 802.11 radios, one small radio same as the ordinary nodes and one powerful radio with power range 800m and channel bandwidth 5Mbps. The mobility model is "group mobility" as presented in [19]. 30 CBR pairs on top of UDP are used to generate the traffics. The scope of backbone election is set to 2-hop. We increase the node mobility from 0m/sec to 10m/sec to compare the performance. Results are shown in Figure 8 and Figure 9.

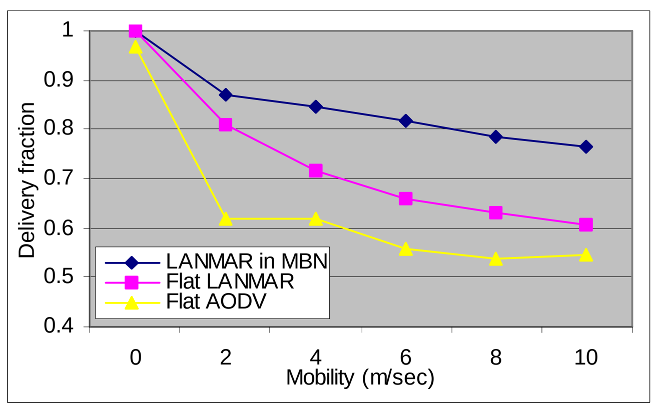


Figure 8 - Comparison of delivery fraction in mobility

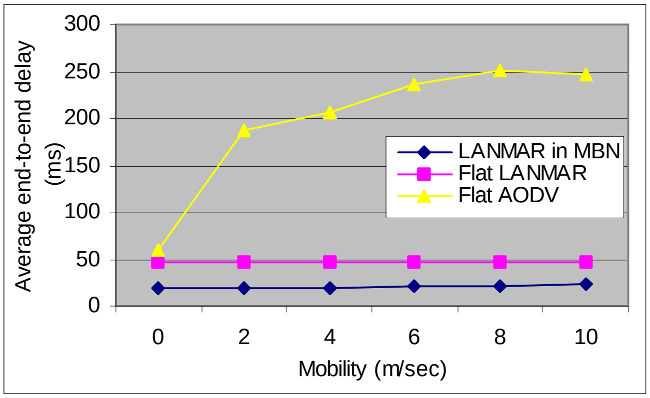


Figure 9 - Comparison of end-to-end delay in mobility

In Figure 8 and Figure 9, LANMAR/MBN outperforms "flat" LANMAR and AODV, especially when nodes move. This is because it utilizes backbone links to reduce the number of hops from sources to destinations. With mobility, the average end-to-end delay of AODV is greatly increased. This is due to the on-demand feature of AODV. For increasing speed, links break and path expire more frequently. AODV then must delay packets as it searches for new paths from sources to destinations. In contrast, LANMAR and LANMAR/MBN are proactive, thus their delay is not affected greatly by the speed. LANMAR in MBN further reduce the delay using backbone links.

7. Related Work

In [12], routing in the UAV based hierarchical structure is investigated. Clustering is also used to select backbone nodes. However, only 1-hop clustering is used. The routing scheme is fully folded onto the hierarchical structure, which centralizes the traffic from each cluster into the corresponding BN, causing potential congestion and single-point-failure problems. In contrast, our scheme of LANMAR/MBN shows advantages in terms of reliability and fault tolerance.

In [9], a traditional on-demand routing scheme is extended to a hierarchical network. The scheme does provide reliability and fault tolerance. To compare it to LANMAR/MBN, let us recall that the latter shows several advantages over "flat" on-demand routing. These advantages still persist in the hierarchical structure. For example, the on-demand hierarchical scheme inherits the long delay of new path discovery, which tends to increase the end-to-end delay of data packets, especially in high mobility. In contrast, the LANMAR/MBN is proactive and thus avoids such a drawback.

8. Conclusions

In this paper we have discussed the critical issues involved in the deployment of Backbone Nodes and the development of a scaleable routing protocol for the MINUTEMAN architecture. The key novelty was the presence of the Mobile Backbone Network (MBN) that must be properly exploited by routing. We have proposed a new stable clustering scheme to deploy the BNs. We have also proposed a LANMAR/MBN routing extension that operates efficiently and transparently with the Backbone network. Backbone links are automatically selected by the routing scheme if they can reduce hop distance to remote destinations. Fault tolerance and system reliability are also considered and achieved. In essence, the proposed scheme combines the benefits of "flat" LANMAR routing and physical network hierarchy. Simulation results using Parsec/GloMoSim platform show that our proposed schemes can establish and operate a MBN effectively and efficiently. It can improve the network performance significantly and it is robust to failures.

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